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The A. & M. College of Texas

Department of
OCEANOGRAPHY AND METEOROLOGY

Research Conducted through the
Texas A & M Research Foundation
COLLEGE STATION, TEXAS

A STUDY OF SPATIAL VARIATIONS IN MICROMETEOROLOGICAL PARAMETERS

Final Report

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Department of Oceanography and Meteorology
College Station, Texas

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Report prepared by

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and

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Research Conducted through the

TEXAS A&M RESEARCH FOUNDATION
College Station, Texas

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PURPOSE

The purpose of this study was to conduct an extensive qualitative and quantitative analysis of spatial variations in micrometeorological variables, using data collected at Hanford, Washington on Contract No. AF 19(604)-4562. The analysis was to be directed toward development of techniques of specifying variability in terms of other meteorological parameters and terrain features, and to include a study of spatial differences in wind and temperature structures and in the heat budget of the earth's surface.

ABSTRACT

This report, aside from a brief review of project tasks, covers a study of the turbulent exchange coefficients based on energy balance and mean flow parameters measured at Project Green Glow. This study reveals that the ratios of the exchange coefficients are functionally related to thermal stability, thereby contradicting those postulates which have assumed constancy of the ratios for all stability situations.

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A. SUMMARY OF PROJECT ACTIVITIES

Three major tasks have comprised the research effort conducted on the subject contract. The first of these was the processing, editing and tabulation of those data collected on Project Green Glow during the summer of 1959 at Hanford, Washington. The results of these efforts, published in 1960, not only made the Green Glow data available to the meteorological community but provided the basic information package for all other project studies as well.

The second task was to seek improvements (by analytical techniques) in the measuring systems and sensors employed at the automatic station (Station 3) used at Hanford since this station would subsequently be used on the Dallas Tower program scheduled to begin in 1961. Resulting system modifications, as well as the activities of the Dallas Tower program, are described in "An Automatic Micrometeorological Data-Collection Station" (1962).

Sensor modification studies, none of which had been completed at the close of the reporting period, can be summarized as follows.

Temperature (copper-constantan thermocouples). The thermal shelters employed for these measurements require improvement, particularly with regard to the wet-bulb measurement, in order to permit capability for use in high humidity environments. This study continues under Contract AF 19(628)-2411.

Insolation and albedo (Eppley pyrheliometer). Comparison studies utilizing five of these devices simultaneously indicates there are questions with regard to the manufacturer's calibration figures, and the ability of the transducers to respond identically over the entire insolation range. This study is nearing completion and will be summarized in a technical report under Contract AF 19(628)-2411.

<u>Net radiation (Beckman-Whitley net radiometers)</u>. Simultaneous sampling from five of these sensors under varying conditions of cloud cover and wind velocity reveals that under certain wind conditions these instruments can differ one to another by as much as 20% and are beyond improvement excepting major redesign. The results of this study are also scheduled for publication under Contract DA 36-039 AMC-02195(E) and Contract AF 19(628)-2411.

<u>Wind direction (Beckman-Whitley wind vane)</u>. It had been tacitly assumed that the wind direction measurements taken at the automatic stations, which consist of an instantaneous value taken each minute, could not be adequate and that an integrating-type of vane should be designed. Testing, however, revealed that 15-minute averages based on the instantaneous values were equivalent, within the capabilities of the sensor itself and known meteorological requirements, to those taken from simultaneous strip-chart measurements. However, since the integrating vane was well past the design stage when these results were determined, an experimental model was completed and found unsatisfactory for usage without costly replacement of standard-quality components by high-precision components.

<u>Wind speed (Beckman-Whitley single-hole chopper anemometers)</u>. These were found to be completely adequate for mean wind speed determinations based on time intervals of no less than four minutes.

Soil heat flux plates (Beckman-Whitley model 190). These sensors are totally unreliable from a design standpoint in that excessive electrical leakage is present between the sensor and the ground except under very dry conditions. Beckman-Whitley has recently redesigned their soil plates to overcome this deficiency and tests are currently underway on three different types of plates to determine the reliability of their usage as direct flux-measuring devices. The results of this study will be published as part of a Master's thesis in August 1963.

The final task covered by this project, covering some two years, consisted of an evaluation of the ratios of the turbulent exchange coefficients based on data from both Green Glow stations. The review of this study, which is presented in Section B, is an abridged version of a doctoral dissertation by Purachand D. Mistry.

B. AN EVALUATION OF TURBULENT EXCHANGE COEFFICIENTS

I. INTRODUCTION

In view of the fact that laminar flow rarely, if ever, occurs in the atmosphere and particularly in the lower layers of the atmosphere, it is not surprising that an understanding of turbulent-flow regime is of primary importance to the micrometeorologist, and considerable effort, both past and current, has been expended toward acquisition of such understanding but with only limited success to date. Such efforts have, of course, produced theories of turbulent flow but with limited application to the atmosphere where the difficulties are multiplied by pronounced diurnal variations which do not, in general, permit one to consider thermal stratification effects as being negligible. Also, unlike the fluid dynamicist or the aerodynamicist, the micrometeorologist is compelled to base his studies on an environment that he cannot control and that is constantly changing.

In actuality, the micrometeorologist could attack many problems of major importance to agriculture, public health, military application, conservation of natural resources, and weather modification, to name only a few, without a complete understanding of turbulent flow if he had understanding of the vertical transport of such atmospheric properties as momentum, sensible heat, and moisture in the turbulent regime represented in the lower layers of the atmosphere. Although it is probable that such understanding cannot be hacked piecemeal from the over-all problems, many such attempts have been made. Efforts in this vein stem from the work of Osbourne Reynolds in 1895 which, though concerned primarily with the transition from laminar to turbulent flow in long straight pipes, demonstrated that the vertical transport of the previously noted properties is definable in terms of mean value departures which necessarily implies (1) that turbulent motion is not dependent on the physical properties of the fluid but rather upon the scale of motion within the fluid, and (2) that in a turbulent regime the instantaneous value of a fluid parameter at a particular point in time and space is composed of a mean value plus an anomaly or departure from the mean. In reality, this equates laminar flow to turbulent flow in the sense that the anomaly is zero in the former flow regime.

This formulation of the vertical fluxes in terms of the anomalies, known as the Reynolds' stresses, has had only limited experimental verification due to instrumentation difficulties. This difficulty plus the implied equivalence of laminar and turbulent flow has led investigators, notably Schmidt (1925) and Prandtl (1934) to seek definition of the vertical transfer in terms of laminar analogy, that is, in terms of the vertical gradient of the mean parameters. These works, which will be referred to again in subsequent sections, lead to the introduction of turbulent coefficients generally referred to as eddy viscosity, eddy conductivity, and eddy diffusivity. Schmidt, who was the first to postulate this analogy, did not show a functional definition of the exchange coefficients nor has any generally-accepted functional definition been advanced by subsequent investigators, although certain gross behavioral patterns of the atmosphere have been defined in terms of the exchange coefficient being constant with height, varying linearly with height, etc. Rather, most studies have been concerned with questioning the extent of the analogy which is the equivalent of asking such questions as "are the exchange coefficients different for different properties?" as would be the case for the laminar counterparts, and "would the ratio of exchange coefficients be constant for all thermal stability situations?" which would not be the case with the molecular counterparts. These are important questions with practical significance, as can be seen by the following example. The Thornthwaite-Holzman evaporation equation which is based on this analogy will yield results that differ by a factor of 50% depending on whether one considers the exchange coefficient ratios to be equal, or to be in the same ratio as their molecular counterparts.

Unfortunately, these questions are still unanswered although numerous examples may be found in the literature to support one of three contentions: that the ratios are unity; that the ratios are constant and equal to the ratios of like molecular coefficients; or that the ratios are not constant. It is the purpose of this study to address itself toward resolution of these questions.

II. BACKGROUND

As previously indicated, Schmidt in 1925 presented a theory of turbulent transfer based on an analogy to molecular transfer and postulated a turbulent transfer coefficient called the Austausch or exchange coefficient. On this basis, considering momentum transfer, the total shearing stress, or vertical momentum flux, is given by

$$\tau = \mu\frac{d\bar{u}}{dz} + A\frac{d\bar{u}}{dz} \tag{2.1}$$

where the terms on the right represent the viscous and turbulent contributions respectively; A is the Austausch coefficient and equal to ρK_m where ρ is the density and K_m is the eddy viscosity; $\bar{u}$ is the mean horizontal wind speed at a given level z. In the atmosphere the turbulent portion of τ is at least greater by a factor of 1000 than the laminar contribution represented by $\mu\frac{d\bar{u}}{dz}$ and the latter can be neglected in the representation for τ.

From the Reynolds' stress definition of the momentum flux and the assumption that the density is constant, K_m may be written as

$$K_m = -\frac{\overline{u'w'}}{\partial\bar{u}/\partial z} \tag{2.2}$$

which clearly shows K_m to be dependent on the scale of motion.

The above definition of the eddy viscosity can be related to the Prandtl mixing length ℓ which is analogous to the mean free path of molecular transfer in that it characterizes a representative distance an eddy will travel before it decomposes and gives up its anomalous properties to modify the mean flow. From the mixing length theory, the eddy shearing stress can be written as

$$\tau = \rho \ell^2 \left(\frac{\partial \bar{u}}{\partial z}\right)\left|\frac{\partial \bar{u}}{\partial z}\right| \tag{2.3}$$

which when equated to (2.1) (minus laminar contribution) relates K_m and ℓ as follows:

$$K_m = \ell^2 \left(\frac{\partial \bar{u}}{\partial z}\right). \tag{2.4}$$

The physical reality of the mixing length is open to considerable question which need not concern us here inasmuch as we shall deal exclusively with the exchange coefficients. However, as equation (2.4) shows, ℓ (at least as a factor of proportionality) can always be evaluated through K_m. The preceding will not be true, however, for ratios of K_m to the exchange coefficients for heat and moisture, inasmuch as it would not necessarily follow that the mixing length for heat or vapor would be the same as that for momentum.

Following the Schmidt concept already shown for momentum flux and ignoring the laminar portions, the vertical fluxes of momentum (τ), sensible heat or convective flux (q_c), and latent heat or evaporative flux (q_e) can be written as

$$\tau = \rho K_m \frac{\partial \bar{u}}{\partial z} \tag{2.5}$$

$$q_c = - \rho C_p K_h \frac{\partial \bar{\theta}}{\partial z} \tag{2.6}$$

$$q_e = - \rho \frac{aL}{p} K_e \frac{\partial \bar{e}}{\partial z} \tag{2.7}$$

where

K_m = eddy viscosity (cm^2/sec),

K_h = eddy conductivity (cm^2/sec),

K_e = eddy thermal diffusivity (cm^2/sec),

$\bar{u}$ = mean horizontal wind speed (cm/sec),

θ = mean potential temperature (°C),

$\bar{e}$ = mean vapor pressure (mb),

z = vertical coordinate (positive upward, cm),

ρ = air density (1.2×10^{-3} gm/cm^3, approximately),

C_p = specific heat of air at constant pressure (.24 cal/gm/deg C, approximately),

a = ratio of molecular weight of water to molecular weight of dry air (.622),

L = latent heat of vaporization (540 cal/gm, approximately),

and the flux units are cal/cm^2/sec.

It is well to emphasize at this point that the exchange coefficients as defined in equations (2.5), (2.6) and (2.7) cannot be questioned as to physical reality *per se* although this question must arise if one attempts to limit this definition by specifying that K_m, for instance, is actually a viscosity or that it is necessarily constant, linear, quadratic, and so on. This point has been made before and is repeated here to emphasize that this study will not concern itself with this question of reality or functional definition of the exchange coefficients but will deal only with the ratios of the coefficients on an empirical basis to seek clarification of assumptions regarding these ratios.

In order to gain insight into these assumptions, it is well at this point to consider some of the quantitative and qualitative aspects before presenting an outline of how this clarification will be sought. Inasmuch as Schmidt's analogy implies transfer of energy in any one of the three forms through the formation, displacement, and decomposition of parcels or eddies of air, it seems reasonable to think of the turbulent exchange coefficients as being a measure of vertical mixing and probably equal to one another if the release of energy from the eddy does not occur until the eddy decomposes and liberates its energy back to the main stream; or, more precisely, as the eddy breaks up it should give up all of its anomaly of momentum, sensible heat and latent heat. However, further thought can show that the eddy coefficients can behave preferentially, thereby affecting the vertical transport of energy, if one considers that the vertical gradient is not the only quantity on which the flux of the appropriate energy depends. For instance, physical inhomogeneities of the bounding surface (the ground) could influence the relative magnitudes of K_h and K_e in conditions of large upward heat transfer. That is, on the surface the sources of heat and vapor need not necessarily be identical, hence different air parcels can have excess heat and excess water vapor and buoyant forces acting preferentially on heated air could cause K_h to be larger than K_e under certain temperature conditions, or K_h to be smaller than K_e in others. Also in a turbulent regime, a fluctuating pressure gradient can alter the momentum of air particles such that momentum does not, in a strict sense of the word, remain a conservative property and K_m need not be equal to K_e or K_h.

An early example of the profitable exploitation of the exchange coefficient concept is to be found in the work of Thornthwaite and Holzman (1939) who assumed the identity of the exchange coefficients and derived a practical formula for estimation of evaporation from a natural surface by using vapor pressure and wind measurements at two heights. The same assumption of identity also forms the basis of the Bowen Ratio approach to the heat budget method of estimation of evaporation although Bowen (1926) did not use it explicitly for this purpose.

Ertel (1942) and Priestley and Swinbank (1947) challenged the equality concept on a theoretical basis by argument that the motion of the eddy affecting the transfer may be influenced by its individual properties and its individual environments and consequently the expression for the flux of a physical property will include, in addition to the term involving the exchange coefficient and the mean gradient of the property, an additional term representing a selective transfer whose magnitude will depend on the fluctuations in the property within the eddy. When applied to vertical transfer of sensible heat this would mean that the exchange coefficient for heat would be greater or less than the exchange coefficient for a neutral property under lapse and inversion conditions respectively, because the warmer eddies will constitute a preferred circumstance.

Businger (1955), commenting on theoretical concepts postulated by Van der Held (1947), based on kinetic theory of gases and molecular analogy, returns to arguments in favor of equality.

Inferences concerning the equality or otherwise of the exchange coefficients drawn from empirical studies are also numerous. Pasquill (1949), from evaporation studies, observed that K_h and K_e, derived from gradients of temperature and moisture, were not equal under unstable conditions. His experiments, however, implied $K_e = K_m$. Rider and Robinson (1951) postulate equivalence on the basis of agreement between the flux determinations by aerodynamic methods which assumes $K_m = K_e$, and by the Bowen Ratio method which assumes $K_h = K_e$.

Rider (1954) obtained values of K_m and K_e on a direct observational basis, and utilized energy balance considerations and equation

(2.6) to obtain K_h, and found that $K_m = K_h = K_e$ over a considerable range of stability although some values of K_h did show exception. The completely opposite conclusion, that is, $K_m \neq K_h \neq K_e$, was arrived at by Swinbank (1955) who measured the fluxes of momentum, heat, and water vapor by observations of the fluctuations of vertical wind, temperature, and water vapor, that is, by Reynolds' stresses computations.

A new phase was added to the controversy by Halstead (1954). Starting with a consideration of the molecular transfer processes occurring at an idealized gas-solid interface, he hypothesized that the effect of turbulent motion is equivalent to the distortion of the successive layers of the gas above the surface which would be planar and of equal area in laminar flow. On the basis of this distortion as representing the physical interpretation of turbulent flow, he derived expressions for τ, q_c, and q_e which state that the ratios of the eddy coefficients are identical to the ratios of their molecular counterparts. Lettau (1957) disagrees with this model (which may be called the "Distorted Area Model") in relation to heat budget measurements, and states that use of predetermined values of exchange coefficient ratios leads to unreliable results. To the contrary, Halstead and Clayton (1957) found that for Project Prairie Grass data during diffusion releases, flux determinations based on the Distorted Area Model fit the energy balance equation to a better degree of accuracy than those determined on the classical basis, that is, where $K_m = K_h = K_e$.

Extension of the question concerning the ratios of K_h to K_m and K_e to K_m, as constant with given stability situations but not constant for all stability considerations, is not too heavily documented in the literature and is for the most part indirect considerations from diabatic profile studies. Examples here are Monin and Obukhov (1954) (logarithmic plus linear), Ellison (1957) (logarithmic plus linear), Clayton, Covey and Merryman (1958) (logarithmic plus 1/2-power), and Elliott (1957) (mixing length variation with stability). All of these studies required the use of a stability term in the diabatic profile relationship which, in turn, requires that these ratios vary with stability. At first thought, inasmuch as the nature of the wind profile in the surface boundary layer is necessarily a function of stability, this would seem to imply that the arguments for equivalence of the exchange coefficients could not be true. However, it is entirely possible that each could vary in the same manner and thus still retain equality.

From the preceding it follows that really only one thing can be said with certainty—the present status of the question is highly confused and further research is required.

III. STATEMENT OF THE PROBLEM

The general problem to be solved with respect to the turbulent exchange coefficients can be stated in question form as follows:

1. Are the three eddy coefficients equal?
2. Are the ratios of K_h to K_m and K_e to K_m equal to constant values? (Of course, ratios of the exchange coefficients could be written in several other ways.)
3. Are the ratios noted above not only constant but equal to specific constants, namely, the ratios of the molecular counterparts?
4. Are the ratios of the exchange coefficients noted above a function of thermal stability in the atmospheric boundary layer?
5. What is the functional definition of the exchange coefficients?

Obviously, these questions are not mutually exclusive.

Resolution of any or all of the five questions noted above requires direct measurements of the shearing stress, the evaporative flux, the convective flux, and many other parameters over a wide variety of stability situations. Unfortunately, no such body of data exists. So in the strict sense of the word, this or any other paper can offer no illumination on the general problem. The strict sense of the word in this case would be "quantitative." A large body of data does exist, however, consisting of indirect measurements of q_c and q_e as well as other required parameters (but not τ) from which qualitative information on all of the questions excepting 5 may be deduced through a negative approach to question 4. That is, if it can be shown that the ratios are not constant but vary with stability, even though quantitatively we do not know what the functional definition of the variability is, then there is little point in asking if questions 2 and 3 are true since obviously they cannot be. If, on the other hand, it should be found that the answer to question 4 is negative, that is, the ratios do not vary with stability, then, again, we may infer answers to questions 1, 2, and 3.

Thus, the statement of the problem as applicable to this study is question 4, from which it will be possible to infer qualitative answers to questions 1, 2, and 3 as well, but not question 5 which must be omitted entirely.

It is believed that the following section on procedure will provide understanding as to why the author has chosen to present the statement of the problem in this rather indirect fashion.

IV. PROCEDURE

If one could have an ideal situation with regard to data type, quality and amount, the solution procedure for the specified problem would be completely straightforward, and in the interests of clarity, we will assume for the moment that this idealization is real. Thus, we assume we have direct measurements of: τ, q_c, q_e, u', w', θ', e' (where the primed quantities indicate anomalies from the mean values of the horizontal wind, vertical wind, potential temperature and vapor pressure, respectively);* and the mean vertical gradients of potential temperature, vapor pressure, and horizontal wind over a wide range of thermal stabilities as classified by the Richardson number which is defined as

$$Ri = \frac{\frac{g}{\theta}\frac{\partial\theta}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2} . \tag{4.1}$$

Mathematically, the above idealization can be represented as follows:

$$\tau_n = \left[-\rho\overline{u'w'}\right]_n = \left[\rho K_m \frac{\partial u}{\partial z}\right]_n \tag{4.2}$$

$$q_{cn} = \left[\rho C_p w'\theta'\right]_n = \left[-\rho C_p K_h \frac{\partial\theta}{\partial z}\right]_n \tag{4.3}$$

$$q_{en} = \left[\frac{a\rho L w'e'}{p}\right]_n = \left[-\frac{a\rho L K_e}{p}\frac{\partial e}{\partial z}\right]_n \tag{4.4}$$

where the subscript n is the thermal stability class index.

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*Henceforth it is understood that any symbol shown without a prime represents the mean value of the given parameter.

As is always the case, the real situation falls short of the ideal, and in fact, not one single parameter listed in the ideal concept can be reliably measured by methods currently available. What can be measured are temperature, at several levels, which through equations (4.5) and (4.6) can yield θ and $\partial\theta/\partial z$;

$$\frac{1}{\theta}\frac{\partial\theta}{\partial z} = \frac{1}{T}\left(\frac{\partial T}{\partial z} + \Gamma\right) \tag{4.5}$$

$$T = C + 273 \quad , \tag{4.6}$$

where T is degrees absolute, Γ is the adiabatic lapse rate, and C is temperature in degrees Centigrade; wet-bulb temperature at several levels, which through the psychrometric equation can be equated to specific humidity which is directly proportional to the vapor pressure, and inversely proportional to the atmospheric pressure, thus yielding $\partial e/\partial z$; u at several levels to give $\partial u/\partial z$; and atmospheric pressure p. Of course, values of ρ, C_p, L, and a as constants (nearly so) are available.

It is quite obvious that the information in the preceding paragraph is insufficient to provide any insight, qualitative or quantitative, as to the behavior of the ratios of the eddy coefficients, and additional information and techniques are required. In order to see what the nature of the additional information and techniques will be, let us consider the principle of conservation of energy which any energy flux computation must necessarily satisfy.

Meteorologically, this principle may be written as follows:

$$R_n - q_s - q_e - q_c - q_a = 0 \tag{4.7}$$

which states that the net energy flux received on a unit area at the earth's surface must be numerically equivalent to: the energy used to change the temperature of the soil, plus the energy used to evaporate moisture from the surface, plus the energy used to change the temperature of the air in contact with the surface, plus the energy summation involved through precipitation, condensation, chemical changes, advective modification, freezing or thawing of water, etc. The net radiation, indicated by R_n, can be measured as can q_s, the energy flux needed to change the temperature of the soil (soil heat flux), and if we assume q_a, which represents all the other energy changes to be negligible, we may re-write (4.7) as

$$R_n = q_s + q_e + q_c \tag{4.8}$$

as the representative expression for the conservation of energy applicable to the problem at hand, where the sign convention is such that energy moving toward the hypothetical unit area will be positive and energy moving away from the hypothetical area will be negative. From (4.8) it may be seen that if a method exists to determine q_c and q_e in terms of the non-idealized data forms listed above and if at the same time we may relate the determinations of q_c and q_e to K_m as well as to K_h and K_e, we will have all the information necessary to attack the problem as stated.

As noted previously, Halstead (1954) postulated a theory of turbulent flow based on a distorted area concept which we will henceforth refer to as the non-classical concept. The details of this postulate are not contained herein but may be obtained either from Halstead's paper or from a paper by Halstead and Clayton previously cited. The results of these papers, which may be derived by similarity concepts as well, are given below where the second c or h subscript indicates the classical relationship (which assumes that the ratios of coefficients are equal to unity) and the non-classical result (where the ratios are equivalent to the ratios of the molecular counterparts), respectively.

$$q_{cc} = q_{ch}/1.4 \tag{4.9a}$$

$$q_{ch} = .124 \times 10^{-3}(u_{2z} - u_z)(T_{2z} - T_z) \tag{4.9b}$$

$$q_{ec} = q_{eh}/1.6 \tag{4.10a}$$

$$q_{eh} = .240 \times 10^{-3}(u_{2z} - u_z)(e_{2z} - e_z) \tag{4.10b}$$

In equations (4.9a) and (4.10a) the ratios 1.4 and 1.6 represent the ratios K_h to K_m and K_e to K_m, respectively, according to Halstead's postulate that these ratios are exactly equivalent to their molecular counterparts or to the reciprocal of the Prandtl number and the Schmidt number for air. The classical argument, that is, the equivalence of exchange coefficients one to another but not to their molecular counterparts would change the values 1.4 and 1.6 to unity, which of course, then would make the non-classical and classical cases identical.

Equation (4.11) defines q_s of equation (4.8) and is based on the Fourier heat conduction equation where ρ_s is soil density, C_s is soil conductivity, and t is time.

$$q_s = \rho_s C_s \int_0^z \frac{\partial T_s}{\partial t}\, dz \, . \tag{4.11}$$

Equations (4.1) and (4.8) through (4.11) provide the analytical tools and in essence, though not explicitly, outline the procedure that will be followed.

Tacitly, it has been assumed that the necessary data exist and such is the case, the specific data being those collected on Contract AF 19(604)-5527 by Texas A&M Research Foundation Project 193 on the Green Glow diffusion experiments at Hanford, Washington during June to August of 1959. However, as evidenced in the background section, there have been other data employed and the question arises as to why this particular data set has potential beyond further confusion of the situation. There are several factors to consider in this vein. These data, published in 1960, were collected at two different sites (called Station 2 and Station 3) and by different methods though utilizing the same type of sensors. Full details on the design and operation of these stations as well as on the processing procedures are contained in a report by Clayton and Merryman (1960) but it is important to note that Station 3 data were collected from an automatic micrometeorological station with simultaneous digital readout and data storage as parameter values ready for analysis, whereas Station 2 data were recorded on strip-charts and suffered subsequent subjective processing before being in a form equivalent to that of Station 3.

Thus we have data collected at two different sites in virtually the same environment, collected by different methods, in sufficient quantity and quality (the data were collected on an essentially continuous basis) and covering a wide stability range. Also, it is important to note that although Project Green Glow had many objectives, one specific objective was the particular study described herein.

Thus, sufficient data exist to provide the basis for the attack on the outlined problem, and it is now possible to summarize the procedural techniques actually employed. This is perhaps best done by considering the equations listed as the analytical tools, that is, equations (4.1) and (4.8) through (4.11).

The Richardson number as defined in equation (4.1) was obtained from measurements of temperature and wind speed at the 1/2 and 2-m levels above the surface, by means of digital computers inasmuch as all the information is contained in punched cards. Values of the convective heat flux and the evaporative heat flux were computed by digital techniques using equations (4.9a) through (4.10b) with the values of u, T and e supplied in two separate ways: first, directly measured values at 1/2, 1 and 2 m (averaged over five minutes for Station 3 data and fifteen minutes for Station 2 data); second, values of u, T, and e from profiles based on measurements at 1/4, 1/2, 1, 2, 4, 8, 16 and 32 m, where the profile was determined as the best linear fit to these levels utilizing the least mean squares technique, and with the fitting being done on a general purpose analog computer.

Soil heat flux values, as defined in equation (4.1), were computed from soil temperatures collected at 3, 6, 12, 25, 40, 65 and 100-cm depths within the soil with ρ_s and C_s being determined separately as soil constants for the particular environments. Directly measured values of q_s also were available and will be discussed subsequently.

The convective flux and the evaporative flux as shown in equations (4.9a,b) and (4.10a,b) as noted earlier are based on the Halstead or non-classical concept and the classical concept (the exchange coefficients are equal) and it might appear that the point which the author is trying to prove it being assumed. This is not the case, of course, since the objective is to evaluate the truth of the postulates of non-classical and classical concepts as will be revealed by satisfaction or lack thereof of equation (4.8).

The preceding is intended only to summarize the procedural techniques that were employed and this discussion will be augmented in the following section which discusses the data analyses and the results obtained.

V. DATA ANALYSIS AND RESULTS

a. Soil Heat Flux

Soil heat flux data (q_s) were measured directly in the Green Glow program and such measurements, if reliable, would make q_s computations by equation (4.11) unnecessary. However, it was pointed out in the Green Glow data report that examination of the sensors following the close of the data-collection period had revealed electrical leakage from sensor to ground that could have been present for most of the data-collection period, and the soil heat plate measurements should be used with great caution. Consequently, the first step in the reduction of the data was to investigate whether the measured values of q_s could be used with confidence in the energy balance computations. This was done by taking 100 cases at random from Station 2 and 100 cases from Station 3 and computing the soil heat flux on the basis of equation (4.11) and then comparing the values against the simultaneous measured values. The calculated values of q_s were arrived at in the following manner.

In equation (4.11) it is assumed that ρ_s and C_s are constant and the assumption is justified both on the basis of measurements of ρ_s made at the site and by the uniformity of color, texture and structure of the soil profile in the region of the soil temperature measurements. The latter is evident from the following abstract from Kocher and Strahorn (1919):

> Winchester fine sand is a dark-gray to brownish-gray, loose fine sand to an average depth of about 12 inches. The subsoil is a dark brownish-gray to grayish-brown, loose fine sand resting on a waterworn gravel at a depth of 3 feet or more . . . . Both the soil and subsoil are low in organic matter and porous and incoherent, though subsoil is more compact.

Measurements of the bulk density and moisture content in the soil at the observation site gave values of ρ_s ranging from 1.5 to 1.7 gm cm^{-3} and of moisture content ranging from 0 to 4% throughout the observation period. In the calculations, the values $\rho_s = 1.675$ and $C_s = .20$ cal/gm/deg C, which were supplied by the Hanford Atomic Products Operation Division of the General Electric Company, were used.

Implicit in the development of equation (4.11) is the requirement that the limit z of the integral is the depth at which the rate of change of temperature with time is identically zero for the time interval under consideration. It would seem reasonable to expect that this requirement would be met at 1 m, which was the maximum measured depth at Green Glow, but the data do not bear this out. Although the time variation of temperature at 1 m was only on the order of a few hundredths of a degree, such differences would be significant in the computations and while it was possible that the differences might be due to errors in the measuring systems at the two stations, examination of the data as well as extrapolation of measured profiles supported the contention that the temperature variations with time at 1 m were real and that the zero difference point occurred at approximately 120 cm. Therefore, $z = 120$ cm was taken as the upper limit of the integral for computations of the soil heat flux.

Of course, equation (4.11) cannot be used in the integral form but must be reduced to a finite-difference form for computational procedures as follows.

$$q_s = \frac{\rho_s C_s}{\Delta t} \sum^{i} (\Delta T_s \Delta Z)_i \qquad (5.1)$$

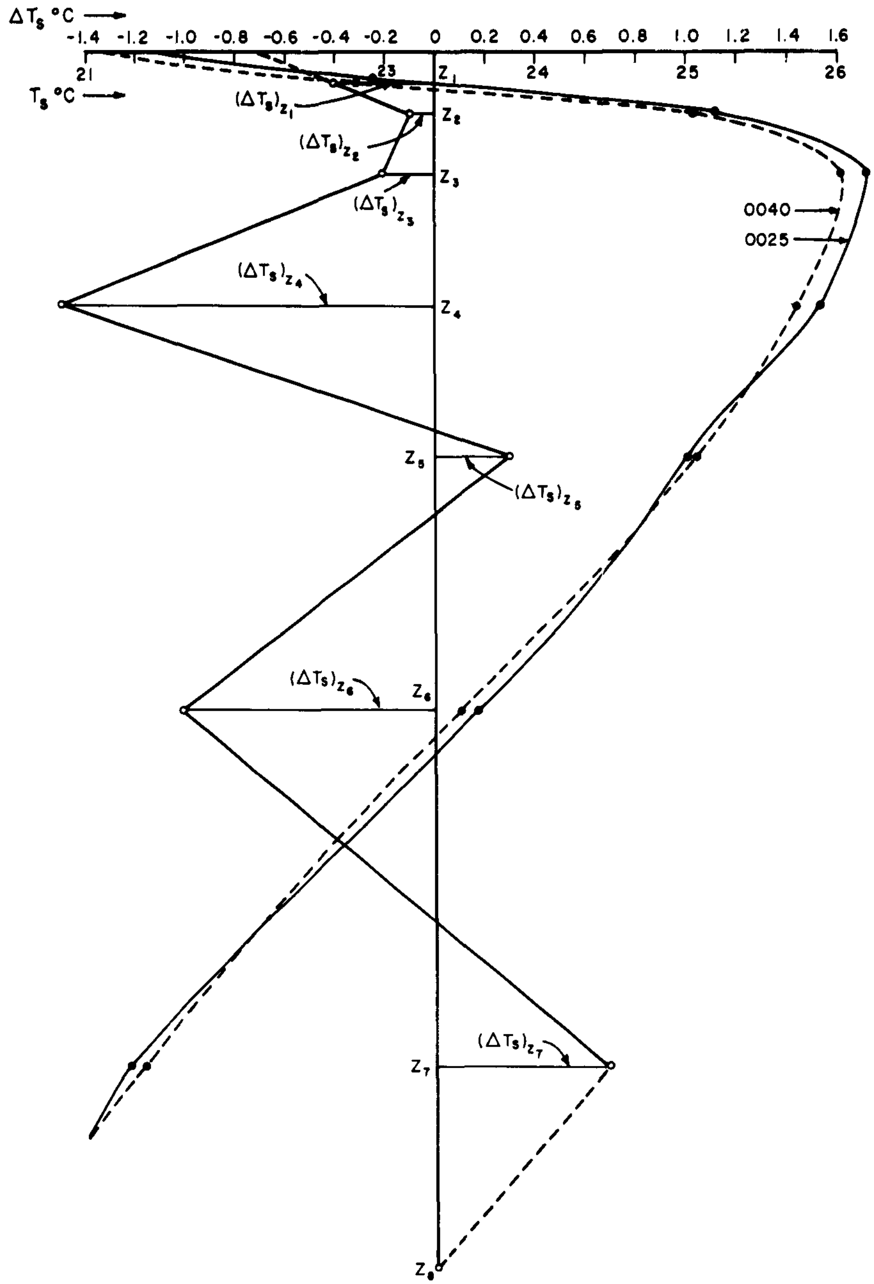
All the computations based on (5.1) were performed by machine methods. However, a graphical equivalent exists which is illustrated in Fig. 1. In this figure the soil temperature difference (ΔT_s) at each level for the time interval (Δt) is plotted as the abscissa against depth z as ordinate, and it is assumed that: the temperature difference between any two successive levels varies linearly with depth; the temperature difference at the surface can be defined by linear extrapolation of the temperature differences slope of the two uppermost levels of measurement and, as noted above, the temperature difference at a depth of 120 cm from the surface is always zero. A modified trapezoidal rule is then applied, resulting in

$$q_s = \frac{\rho_s C_s}{(\Delta t)} \Big[6.0(\Delta T_s)_{z_1} + 3.0(\Delta T_s)_{z_2} + 9.5(\Delta T_s)_{z_3} + 14.0(\Delta T_s)_{z_4} + 20.0(\Delta T_s)_{z_5} + 30.0(\Delta T_s)_{z_6} + 27.5(\Delta T_s)_{z_7} \Big] \qquad (5.2)$$

which is the actual computational form of (4.11) and (5.1). In this equation $(\Delta T_s)_{z_3}$ indicates the temperature difference in hundredths of a degree Centigrade at the level z_3 (12 cm), etc.

It should be noted that equation (5.2) was not blindly chosen as a computational scheme. Several other methods using rectangular addition, Simpson's rule, and a planimeter were compared and from these comparisons the method represented by (5.2) was found to be completely adequate. The example in Fig. 1 includes a planimeter solution for the same data as well as the corresponding direct heat flux measurement.

In the initial testing of the values of the measured soil heat flux versus calculated heat flux, a ΔT of five minutes was used inasmuch as the basic data group from the automatic station (Station 3)



SAMPLE GRAPHICAL SOLUTION FOR q_s – JUNE 26, 0025-0040

SOIL HEAT FLUX VALUES–

CALCULATED BY GRAPHICAL INTEGRATION

TRAPEZOIDAL METHOD $= -0.0034 \frac{\text{CAL}}{\text{CM}^2\,\text{SEC}}$

PLANIMETER $= -0.0032 \frac{\text{CAL}}{\text{CM}^2\,\text{SEC}}$

MEASURED BY FLUX PLATE $= -0.00012 \frac{\text{CAL}}{\text{CM}^2\,\text{SEC}}$

FIGURE 1

was in five-minute periods. However, the results were for the most part just as bad as the single example shown in Fig. 1 and it was felt at this point that perhaps a longer averaging period might bring the two methods into better agreement and the averaging period for Station 3 data was lengthened to 15 minutes while that at Station 2 was lengthened to 30 minutes. Increased averaging time, however, was not the answer and, as can be seen from Table 1, measured soil heat values and calculated soil heat values did not agree within orders of magnitude and even though there was every reason to believe that the measured values were in error, there seemed nothing else to do except to compute a set of calculated heat flux values for all cases and then to investigate the energy balance on the basis of both measured and calculated q_s values.

b. Convective and Evaporative Flux

The values of these fluxes were obtained through direct use of equations (4.9a) and (4.10a) for the classical cases and the corresponding non-classical values through (4.9b) and (4.10b).

However, these equations were employed in two ways, or more specifically, the non-classical heat flux was computed first using direct measurements at specific levels and second using the u, T, and e values determined from the line of best fit to the profiles for a given time interval. There were two reasons for this procedure. First, for practicable applications of flux determinations in such pursuits as agriculture, military planning, etc., it is not likely that detailed profiles of wind, temperature, and vapor pressure can be made, and the more likely situation would be that information would be available for

Table 1. Statistical analysis of calculated and measured values of soil heat flux.

Station	Mean Difference*	Deviation	Standard Error of Mean Difference	t-test Value	Significance
3	58.85×10^{-5} cal $cm^{-2}sec^{-1}$	175.22×10^{-5} cal $cm^{-2}sec^{-1}$	17.522×10^{-5} cal $cm^{-2}sec^{-1}$	3.358	Significant at 1% level
2	57.99×10^{-5} cal $cm^{-2}sec^{-1}$	181.71×10^{-5} cal $cm^{-2}sec^{-1}$	18.171×10^{-5} cal $cm^{-2}sec^{-1}$	3.191	Significant at 1% level

*This is based on the calculated minus measured value of soil heat flux for 15-minute periods for Station 3 and 30-minute periods for Station 2.

only two levels, which is implied as sufficient in equations (4.9) and (4.10). The question arises as to where these levels should be, inasmuch as the equations require only that one level be twice as far from the ground as the other. Second, no matter what the level selection might be, as is discussed below, what would be the differences that would be involved in the flux terms if the full profile values were utilized rather than discrete levels? The use of profiles assigns equal weight to each level of measurement, and hopefully would rule out most of the instrumental error, but would introduce bias inasmuch as it is well known that the vertical profiles of temperature, wind, and vapor pressure, though tending to be logarithmic in neutral stability, are very definitely influenced by buoyancy such that departure from the logarithmic profile is the rule for non-neutral stability. (Of course, it was the general knowledge of occurrence of near-logarithmic profiles that led to selection of the levels of measurement that were employed in Project Green Glow.)

Thus the selection of the levels of measurements utilized in the discrete level computations merits careful consideration. In order to satisfy the assumptions involved in the derivation of the flux equations to the greatest possible extent—the lowest level must be sufficiently far away from the surface as to avoid effects of surface irregularities—the two selected levels must be adequately far apart to minimize instrumental and sampling errors, while the top level must not be so far from the surface that it will be subject to the effects of buoyancy.

Three pairs of levels—50 to 100 cm, 100 to 200 cm, and 50 to 200 cm—offered the best compromise to the requirements and were selected for computations of q_c and q_e by both the classical and non-classical methods. For the computations based on 50 to 200 cm, the constant multipliers of the flux equations were adjusted appropriately.

For the computations of the evaporative and convective heat fluxes by profile methods, some thought was given as to whether all eight measuring levels should be used inasmuch as buoyancy effects would very definitely be most pronounced for the upper levels and perhaps should be ignored. On the other hand, consideration of only the lower four or five levels, where the spacing is closer, would magnify instrumental errors. No clear resolution of this question was possible. However, on the basis of hand calculations, covering twenty-five cases, it was found that although individual flux values would be altered from the consideration of the four lower points versus all eight points, the over-all distribution was not. Consequently it was decided that the computations would be based on the full profiles where the best logarithmic fit, utilizing the principle of least mean squares, would be assumed as the true profile for temperature, wind, and vapor pressure. These computations were performed on a general purpose analog computer which was so programmed that the individual measured points were simultaneously plotted in a series of straight-line segments with the line of best fit then plotted through the segments so as to provide a visual check on the least squares fit and at the same time provide a qualitative record of the differences between the consideration of only the four lower measured points versus the full profile.

At this point in the study we have both calculated and measured soil heat flux values, convective and evaporative heat fluxes on the classical and non-classical basis from three discrete level measurement points as well as full profiles, net radiation by direct measurement, and it would seem we would be ready to investigate energy balances in order to pursue the basic aims of the problem. However, in the actual execution of the research two additional factors came to light that postponed energy balance investigation. These were (1) wide scatter of the coordinate points represented in equation (4.8) where R_n and the summation q_s, q_c and q_e comprise the coordinate points, and (2) impossible-data situations, that is, where the summation of the fluxes would be of opposite sign to R_n. Clearly, both of these factors must result from measurement limitations and a secondary study was begun to determine the source and magnitude of the measurement errors.

It had been pointed out in the Green Glow data report that wet-bulb temperature determinations were probably suspect on some occasions due to inadequate wetting of the wick around the wet-bulb thermocouple but a quantitative evaluation of this type of error was not known. This could mean, then, that the q_e determinations were likely to be a contributing factor in the wide-scatter and impossible-data cases. However, this did not seem to be the complete answer and a more careful study of the reliability of direct measurements of net radiation was instituted. Fortunately, a measuring program similar to that at Hanford was currently underway near Dallas, Texas (the Dallas Tower Program) utilizing the same type of sensors employed at Green Glow, and tests were begun to determine the degree of variability between five such sensors when exposed to the same radiation environment. These tests, conducted by Texas A&M Research Foundation Project 256, quickly revealed that differences up to 20% between the sensor outputs could occur under certain wind conditions, with the worst situation occurring when the wind was of such direction as to oppose the aspiration provided for these instruments, particularly so if strong gustiness was also present. It was also found that, contrary to the manufacturer's specifications, the best measurements were obtained from these sensors when the wind was crosswind to the aspiration rather than downwind. These two measurement defects were more than adequate to explain the wide scatter and impossible values and whereas no question was involved as to what to do with the impossible data (they were eliminated), a technique was sought to exclude wild, though possible, cases remaining without introducing subjectivity into the analysis.

The method finally selected was utilization of the Bowen Ratio (β) which is the ratio of q_c to q_e. Normally this ratio will not exceed .2 or .3, which is the equivalent of saying that the evaporative heat flux is, under normal circumstances, much greater than q_c. Inasmuch as the Hanford, Washington environment, in which the Green Glow measurements were made, is semi-arid, it seemed reasonable to suppose that the

Bowen Ratio might be higher than .3 but certainly not higher than by a factor of 10. On this basis, Bowen ratios were computed for all data and those yielding Bowen Ratio values in excess of 3 were discarded.

c. Energy Balance

The results of the energy balance computations satisfying equation (4.8), which may be rewritten as y = mx where y = the net radiation and x = the total of constituent fluxes, are summarized in tables 2 and 3 with Table 2 applying to Station 2 and Table 3 to Station 3. It will be noted that for Station 3 the profile computations were terminated after the first 85 cases inasmuch as it could be seen at this point that the trend for the two stations was the same even though they were at different locations, with the measurements made in different fashion and with different averaging periods (30 minutes for Station 2 and 15 minutes for Station 3), and there seemed little point in spending an additional three to four months getting the additional profile cases even if the general purpose analog computer could be made available on a full-time basis for this period. As indicated in tables 2 and 3, the results of two profile cases for each table are plotted in Fig. 2-5. The line of best fit shown for the various cases in tables 2 and 3 has been fitted by least squares with the requirement that the regression line pass through the origin. The Bowen Ratio exclusion concept already noted was not applied to the analysis shown in tables 2 and 3 (and in Fig. 2, 3, 4, and 5) but was to all subsequent analyses. The reasons for imposing the exclusion at this point in the computations will be discussed later.

Tables 4 and 5 show the breakdown of the profile cases only into

Table 2. Results of energy balance at Station 2

Method	Appropriate Totals of Constituent Heat Fluxes	Pair of Levels (m)	Line of Best Fit	No. of Cases	See Fig. No.
Non-classical	$q_{ch} + q_{eh} + q_{scal}$	0.5-1.0	y = 1.62x	63	--
"	"	1.0-2.0	y = 1.51x	106	--
"	"	0.5-2.0	y = 1.12x	81	--
Classical	$q_{cc} + q_{ec} + q_{scal}$	0.5-1.0	y = 2.04x	47	--
"	"	1.0-2.0	y = 0.99x	82	--
"	"	0.5-2.0	y = 1.5x	57	--
Non-Classical	$q_{ch} + q_{eh} + q_{sm}$	0.5-1.0	y = 2.35x	267	--
"	"	1.0-2.0	y = 1.42x	266	--
"	"	0.5-2.0	y = 1.77x	285	--
Classical	$q_{cc} + q_{ec} + q_{sm}$	0.5-1.0	y = 3.34x	270	--
"	"	1.0-2.0	y = 1.36x	267	--
"	"	0.5-2.0	y = 2.19x	304	--
Non-classical	$q_{ch} + q_{eh} + q_{scal}$	Entire Profiles	y = 0.54x	410	2
"	$q_{ch} + q_{eh} + q_{sm}$	Entire Profiles	y = 0.50x	410	--
Classical	$q_{cc} + q_{ec} + q_{scal}$	Entire Profiles	y = 0.79x	410	3
"	$q_{cc} + q_{ec} + q_{sm}$	Entire Profiles	y = 0.77x	410	--

y = net radiation

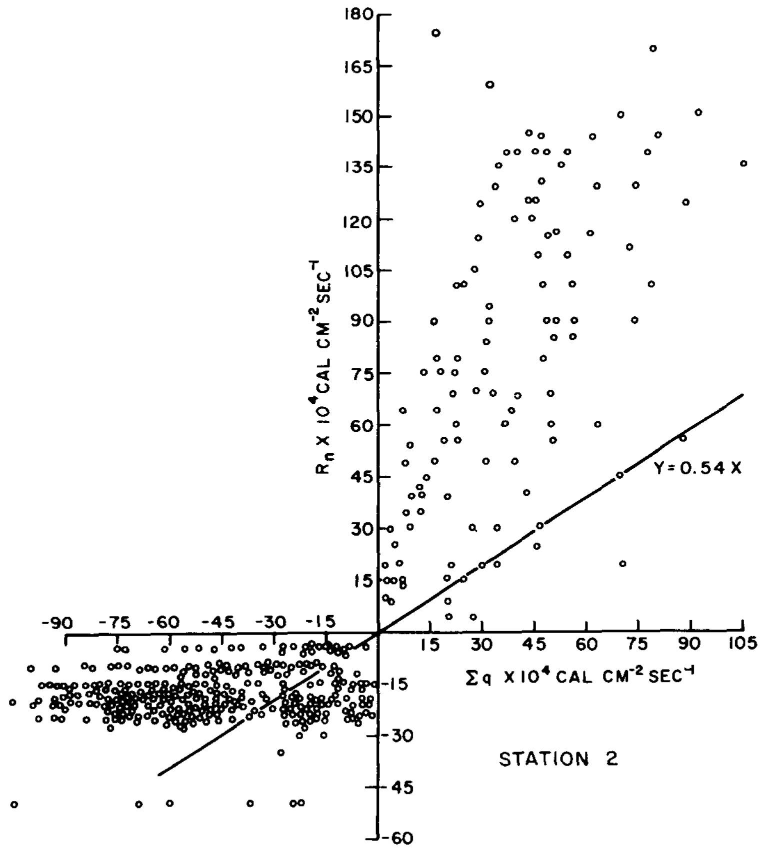
x = total of constituent fluxes

Table 3. Results of energy balance at Station 3.

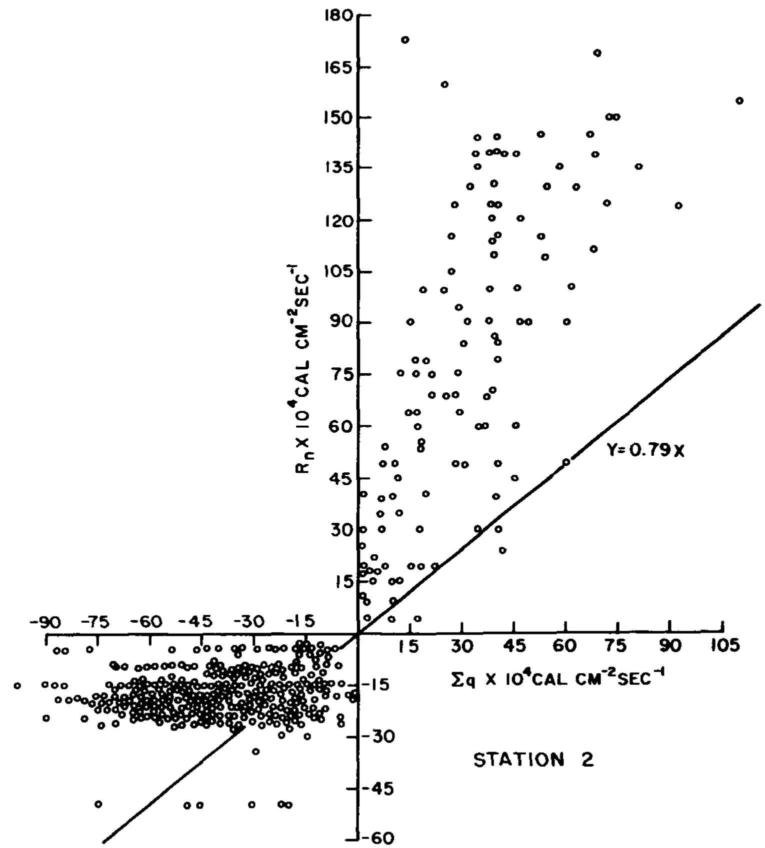
Method	Appropriate Totals of Constituent Heat Fluxes	Pair of Levels (m)	Line of Best Fit	No. of Cases	See Fig. No.
Non-classical	$q_{ch} + q_{eh} + q_{scal}$	0.5-1.0	y = 1.60x	1069	--
"	"	1.0-2.0	y = 0.77x	1114	--
"	"	0.5-2.0	y = 1.31x	1199	--
Classical	$q_{cc} + q_{ec} + q_{scal}$	0.5-1.0	y = 2.28x	1122	--
"	"	1.0-2.0	y = 0.91x	1152	--
"	"	0.5-2.0	y = 1.72x	1219	--
Non-classical	$q_{ch} + q_{eh} + q_{sm}$	0.5-1.0	y = 1.48x	848	--
"	"	1.0-2.0	y = 0.74x	1063	--
"	"	0.5-2.0	y = 1.35x	1146	--
Classical	$q_{cc} + q_{ec} + q_{sm}$	0.5-1.0	y = 2.10x	832	--
"	"	1.0-2.0	y = 0.86x	1072	--
"	"	0.5-2.0	y = 1.68x	1140	--
Non-classical	$q_{ch} + q_{eh} + q_{scal}$	Entire Profiles	y = 0.34x	85	4
"	$q_{ch} + q_{eh} + q_{sm}$	Entire Profiles	y = 0.56x	85	--
Classical	$q_{cc} + q_{ec} + q_{scal}$	Entire Profiles	y = 0.80x	85	5
"	$q_{cc} + q_{ec} + q_{sm}$	Entire Profiles	y = 0.43x	85	--

y = net radiation

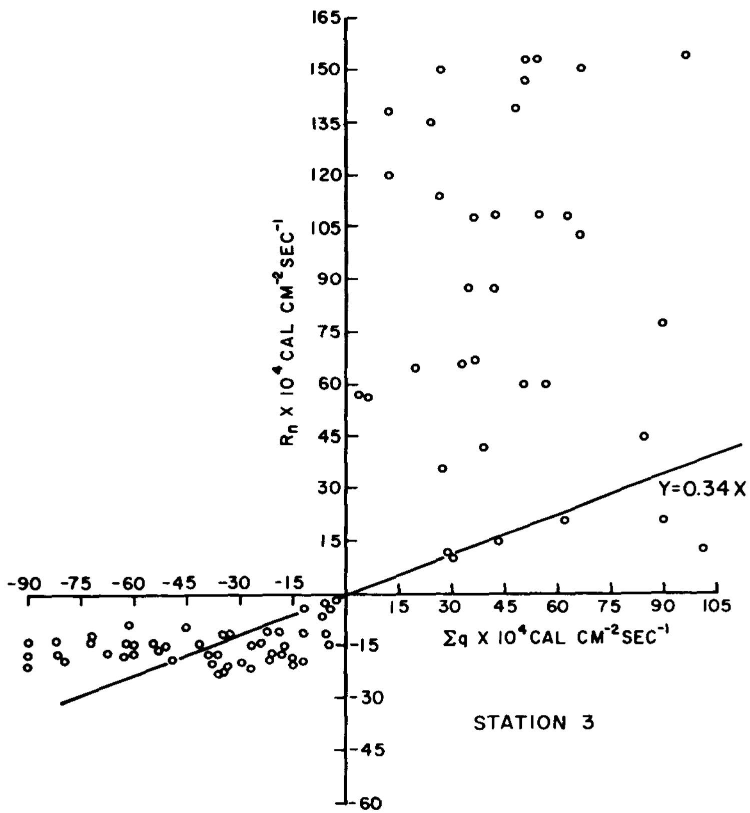
x = total of constituent fluxes



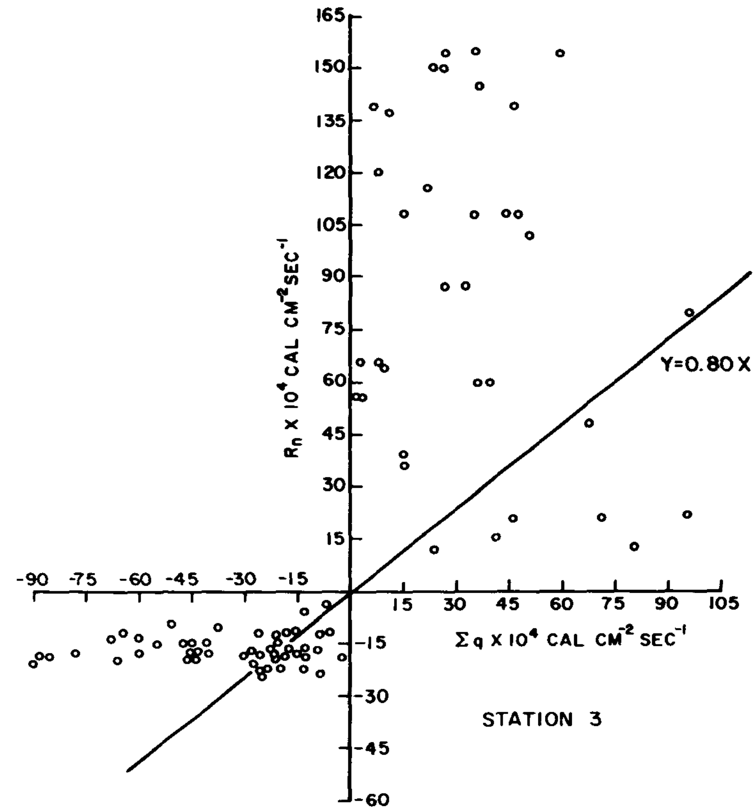
ENERGY BALANCE BASED ON ENTIRE PROFILES
NONCLASSICAL
FIGURE 2



ENERGY BALANCE BASED ON ENTIRE PROFILES
CLASSICAL
FIGURE 3



ENERGY BALANCE BASED ON ENTIRE PROFILES
NONCLASSICAL
FIGURE 4



ENERGY BALANCE BASED ON ENTIRE PROFILES
CLASSICAL
FIGURE 5

Bowen Ratio classifications with a further breakdown into day and night classifications according to both the classical and non-classical concepts. The particular intervals used are of no special merit except it was felt that Bowen ratios of the order of zero to .5 or possibly zero to 1.0 would probably represent the actual situation the majority of the time, and the same interval subdivision was then followed up to a Bowen Ratio value of 3, beyond which it was assumed that an impossible situation existed.

As noted in tables 4 and 5, the data have been given for every classification case and Fig. 6 through 9, which represent the summation, retain the classification subdivision in that different symbols are used to plot the different cases.

Tables 6 and 7 show the classification of profile cases by Richardson number for stations 2 and 3 which have been computed from discrete level measurements at 1/2 and 1 m. The separation of the Richardson numbers into the classifications shown as well as the basis of computation from discrete levels rests on the following considerations. There is strong reason to believe that the Richardson number will itself vary with height in non-neutral stability situations and therefore it would not seem reasonable to compute it on the basis of the fitted profiles. Also, all the evidence would indicate that the wind and dry-bulb temperature measurements of the Green Glow data block can be considered reliable to a high degree of significance (though the same cannot be said for wet-bulb determinations); consequently, considering the above noted variation of Richardson number with height, there seems no real justification in assuming that, for these computations, the profile values will be any more significant than

Table 4. Results of energy balance according to Bowen Ratio classification based on profile values —Station 2.

Bowen Ratio	Day-time Cases		Night-time Cases		See Fig.
	Non-Classical	Classical	Non-Classical	Classical	
0.0 - 0.5	y = 1.30x	y = 1.76x	y = 0.38x	y = 0.49x	--
0.5 - 1.0	y = 1.50x	y = 1.93x	y = 0.42x	y = 0.68x	--
1.0 - 1.5	y = 2.42x	y = 2.69x	y = 0.46x	y = 0.41x	--
1.5 - 2.0	y = 2.69x	y = 3.11x	y = 0.35x	y = 0.46x	--
2.0 - 2.5	y = 1.94x	y = 2.33x	y = 0.26x	y = 0.35x	--
2.5 - 3.0	y = 2.19x	y = 2.56x	y = 0.38x	y = 0.49x	--
0.0 - 3.0	y = 1.78x	y = 2.22x	y = 0.38x	y = 0.47x	6-7

y = net radiation

x = total of constituent fluxes

$q_s = q_{s\ cal}$

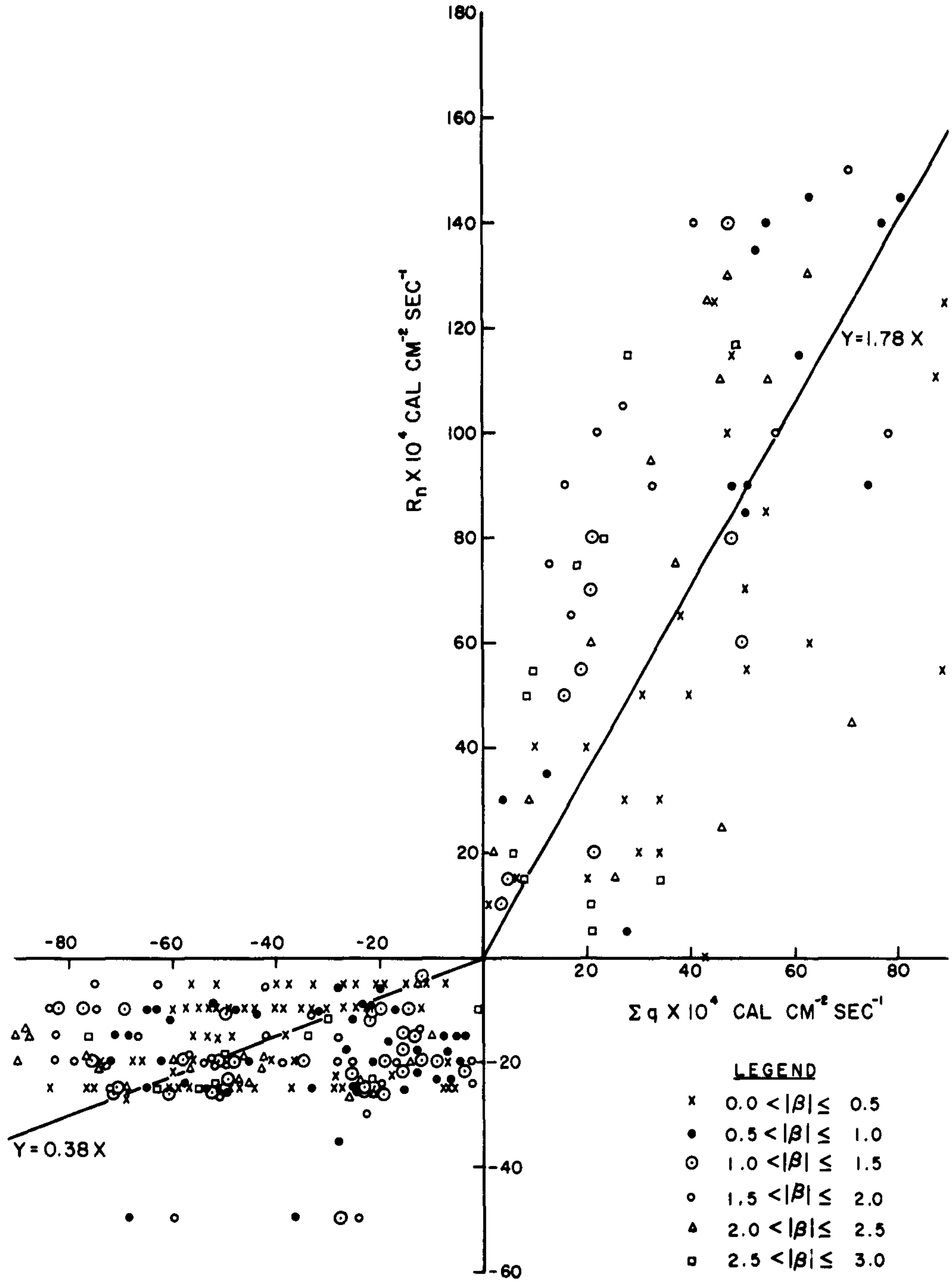
Table 5. Results of energy balance according to Bowen Ratio classification based on profile values —Station 3.

Bowen Ratio	Day-time Cases		Night-time Cases		See Fig.
	Non-Classical	Classical	Non-Classical	Classical	
0.0 - 0.5	y = 1.38x	y = 2.31x	y = 0.41x	y = 0.61x	--
0.5 - 1.0	y = 1.97x	y = 2.77x	y = 0.16x	y = 0.21x	--
1.0 - 1.5	y = 2.73x	y = 3.26x			--
1.5 - 2.0	y = 3.96x	y = 4.60x			--
2.0 - 2.5	y = 2.66x	y = 3.28x			--
2.5 - 3.0	y = 1.95x	y = 2.44x	y = 0.64x	y = 0.85x	--
0.0 - 3.0	y = 2.14x	y = 2.92x	y = 0.33x	y = 0.46x	8-9

y = net radiation

x = total of constituent fluxes

$q_s = q_{3\ cal}$

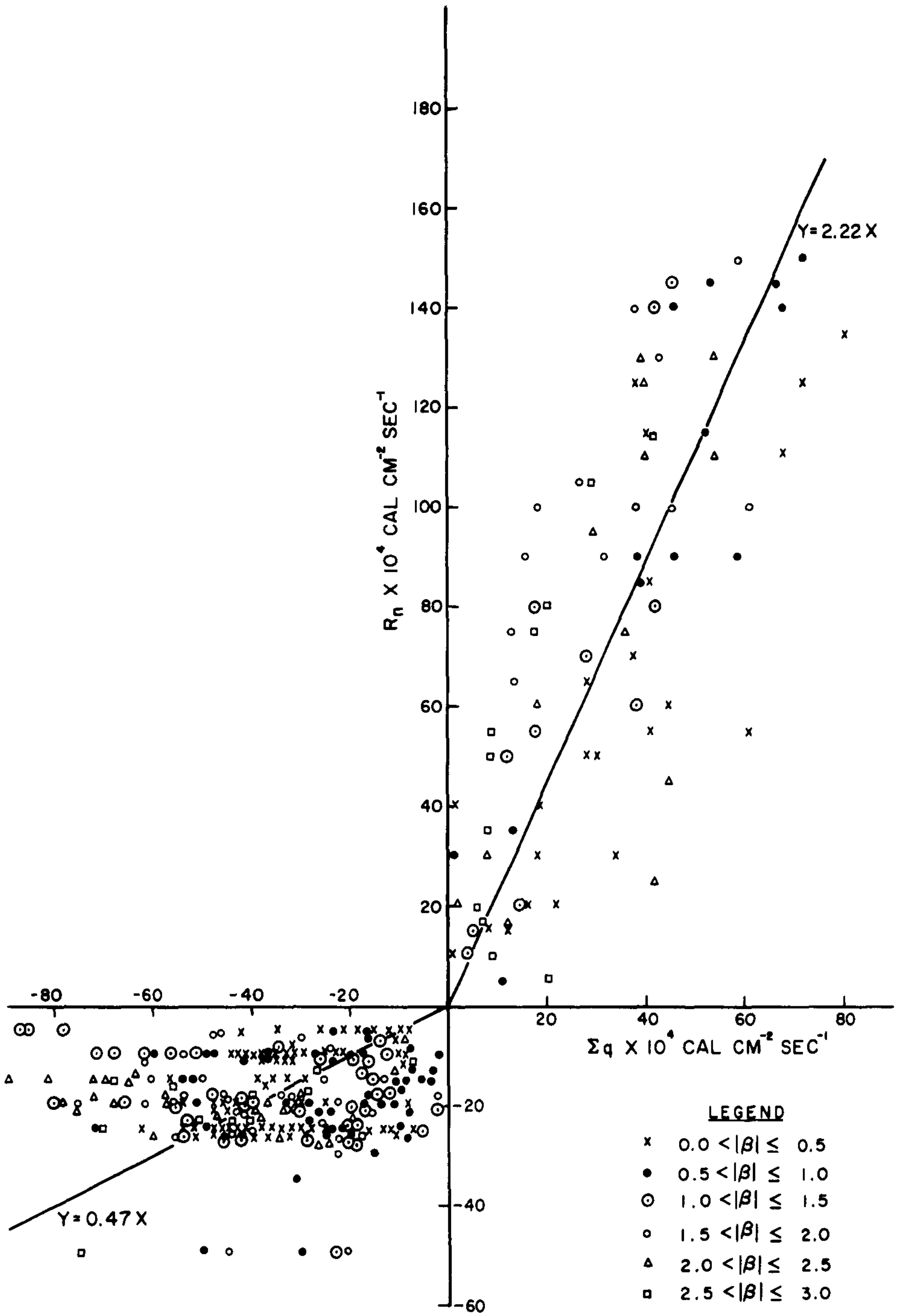


STATION 2

ENERGY BALANCE FOR ALL CASES WITH $-3.0 \leq \beta \leq +3.0$

NONCLASSICAL

FIGURE 6

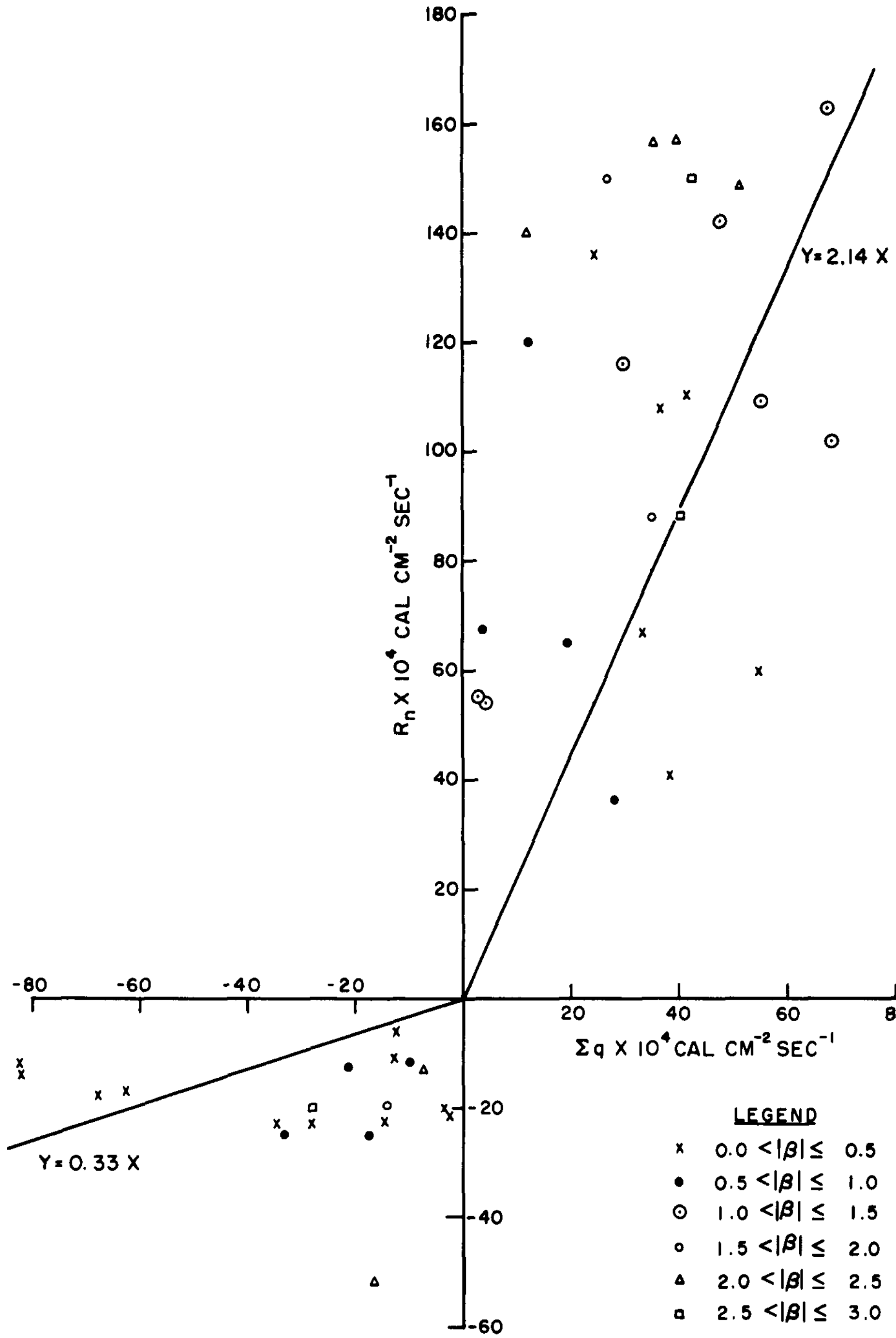


STATION 2

ENERGY BALANCE FOR ALL CASES WITH $-3.0 \leq \beta \leq +3.0$

CLASSICAL

FIGURE 7

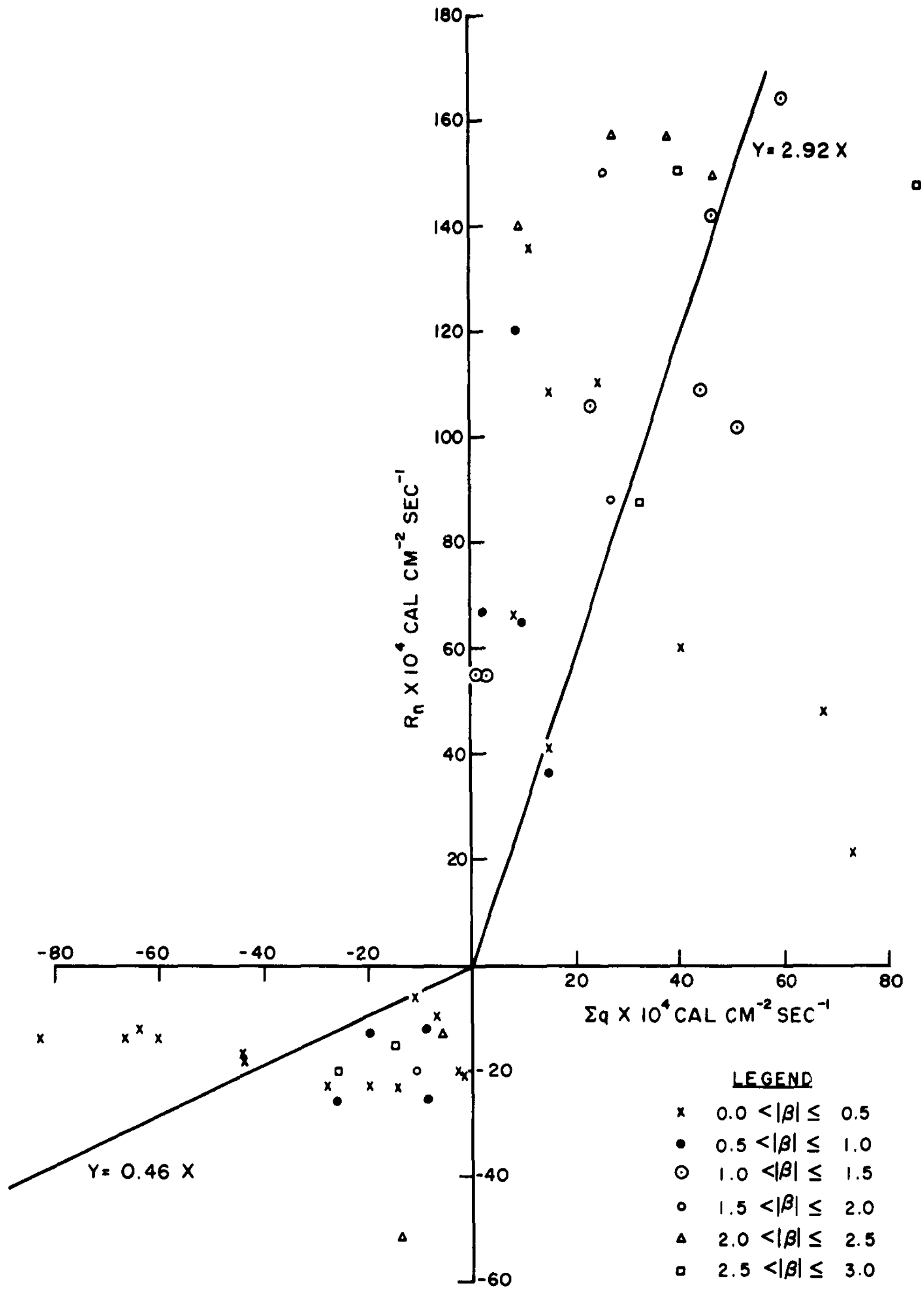


STATION 3

ENERGY BALANCE FOR ALL CASES WITH $-3.0 \leq \beta \leq +3.0$

NONCLASSICAL

FIGURE 8



STATION 3

ENERGY BALANCE FOR ALL CASES WITH $-3.0 \leq \beta \leq +3.0$

CLASSICAL

FIGURE 9

Table 6. Results of energy balance for profile values grouped according to Richardson number—Station 2.

Richardson Number	Non-Classical	Classical	No. of Cases
Ri < -1.0	y = 2.57x	y = 2.71x	5
-0.1 - -1.0	y = 2.36x	y = 2.72x	38
-0.01 - -0.1	y = 2.23x	y = 2.71x	52
0.0 - -0.01	y = 0.17x	y = 0.20x	20
0.0	y = 0.14x	y = 0.18x	22
0.0 - 0.01	y = 0.46x	y = 0.55x	86
0.01 - 0.1	y = 0.29x	y = 0.37x	131
0.1 - 1.0	y = 0.26x	y = 0.32x	41
Ri > 1.0	y = 0.23x	y = 0.30x	5

y = net radiation

x = total of constituent fluxes

$q = q_{s\ cal}$

Table 7. Results of energy balance for profile values grouped according to Richardson number—Station 3.

Richardson Number	Non-Classical	Classical	No. of Cases
Ri < -1.0	y = 4.01x	y = 5.24x	3
-0.1 - -1.0	y = 2.41x	y = 2.98x	10
-0.01 - -0.1	y = 2.47x	y = 3.58x	14
0.0 - -0.01	y = 1.59x	y = 2.22x	8
0.0	---	---	0
0.0 - 0.01	y = 0.33x	y = 0.45x	7
0.01 - 0.1	y = 0.24x	y = 0.34x	12
0.1 - 1.0	y = 0.20x	y = 0.25x	4
Ri > 1.0	---	---	0

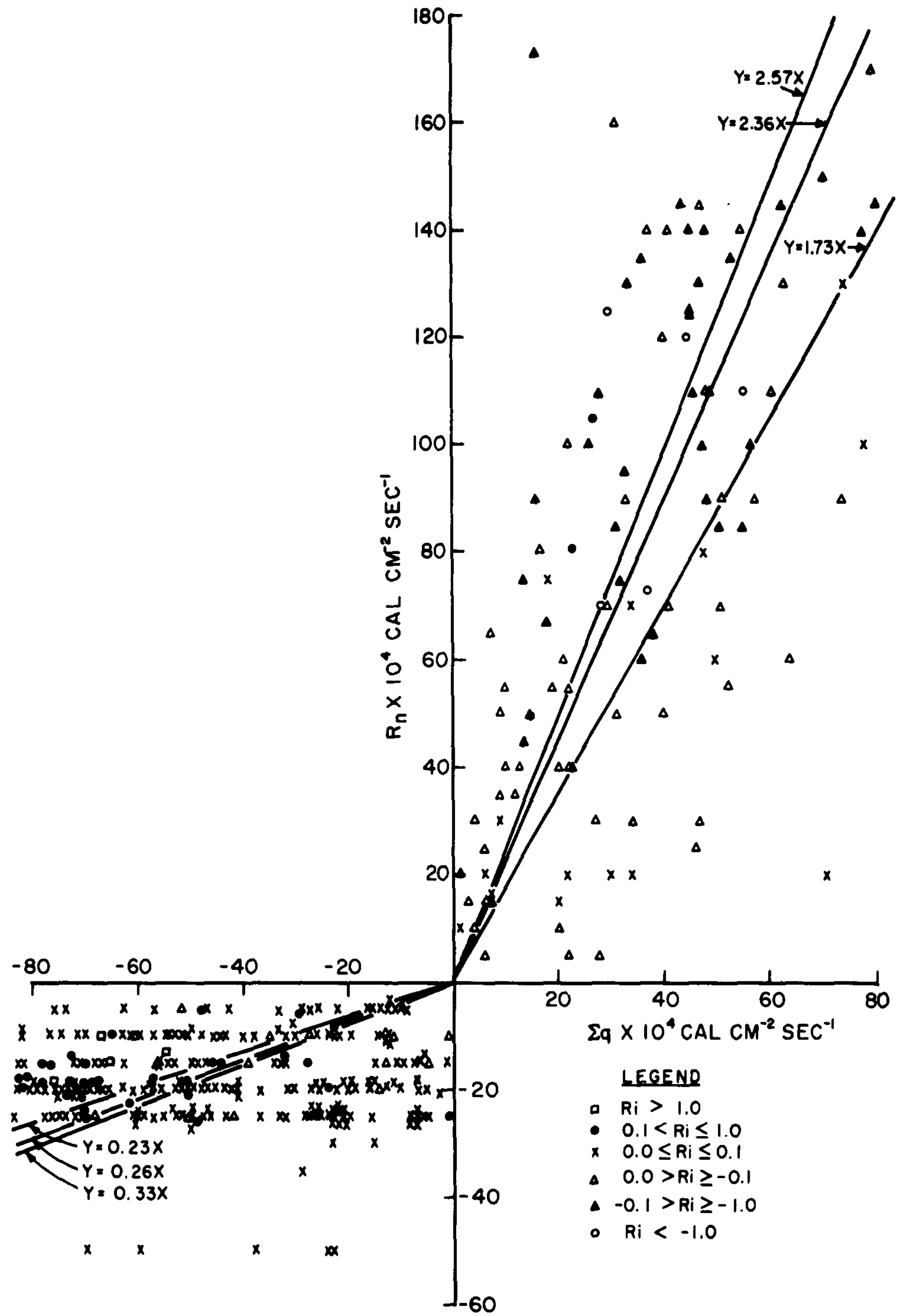
y = net radiation

x = total of constituent fluxes

$q = q_{s\ cal}$

the discrete level measurements. Finally, there seemed little point in subdivision of the Richardson number beyond that necessary to effect separation between stability extremes which are represented.

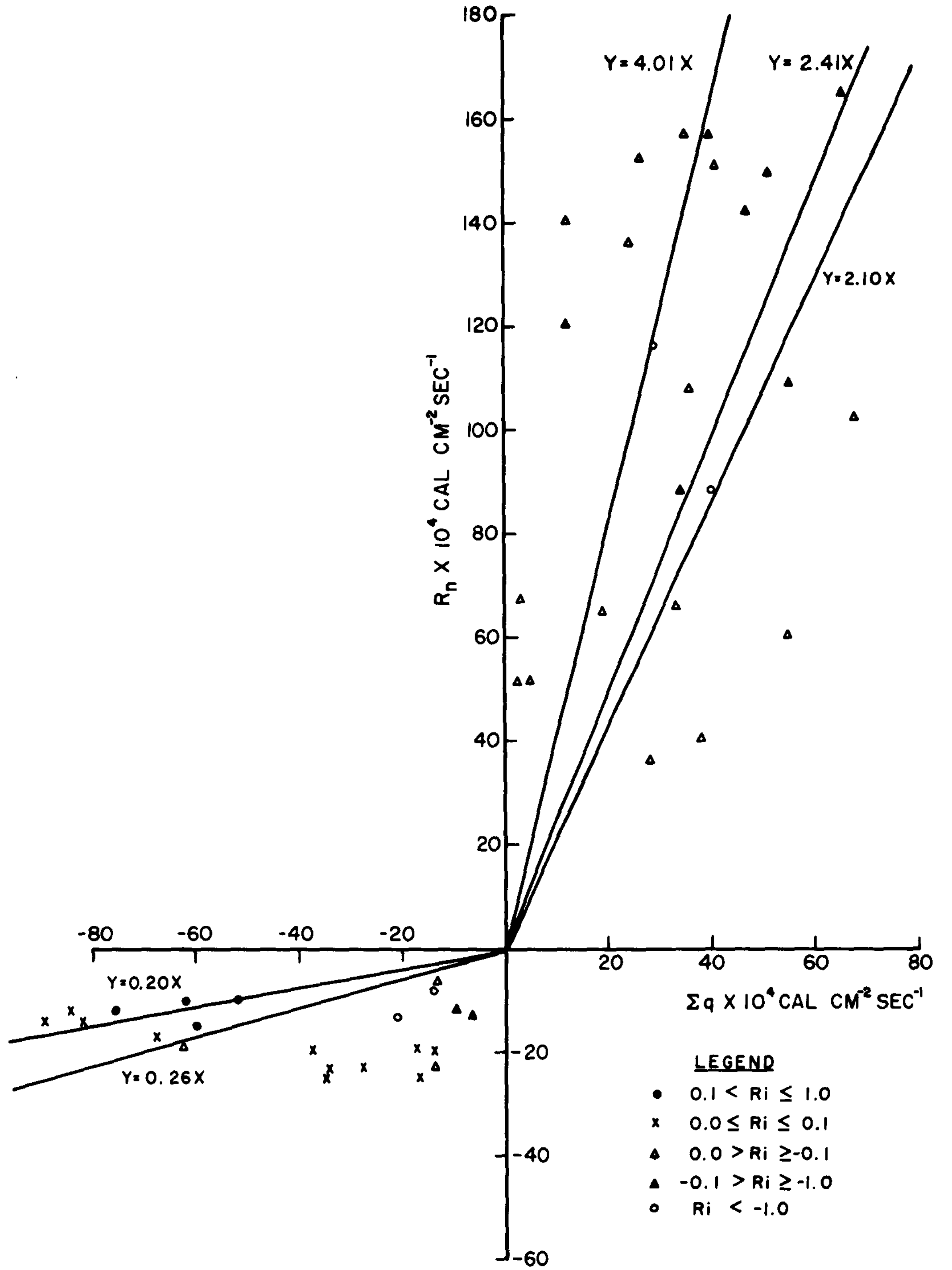
The results of these computations as protrayed in the cited tables and figures will be discussed in detail in the following section but it is apparent from consideration of tables 6 and 7 alone (or from Fig. 10 and 11) that the coefficient ratios vary with stability, which was the basic question involved in this study. Assuming that the Bowen Ratio separation is also a stability classification, which seems reasonable inasmuch as it represents a variation in $\partial\theta/\partial z$ and $\partial u/\partial z$, tables 4 and 5 show this same variation of exchange coefficient ratios with stability.



STATION 2

ENERGY BALANCE GROUPED ACCORDING TO RICHARDSON NUMBER - NONCLASSICAL

FIGURE 10



STATION 3
ENERGY BALANCE GROUPED ACCORDING TO RICHARDSON NUMBER-NONCLASSICAL
FIGURE 11

VI. CONCLUSIONS

The specific problem treated herein, namely, do the ratios of the exchange coefficients vary with stability, is essentially answered by tables 2 and 3 and Fig. 2, 3, 4, and 5, and the remaining tables and graphs supplement the information contained in this first group. However, several other deductions may also be made, bearing not only on the questions concerning the exchange coefficients (see p. 14) that make up the general problem but on measurement and analytical procedures as well.

Let us consider one of the additional results, specifically the use of discrete levels versus profiles for computation of the energy fluxes for evaporative and sensible heat. Looking at tables 2 and 3 and considering any one of the four classifications utilizing discrete levels, it will immediately be seen that each level gives significantly different results for the same computational assumptions and one can clearly reject the use of discrete levels in preference for profile values.

Looking at only the profile computations in these tables, particularly Table 2, one could be inclined to deduce that the classical concept is considerable better than the non-classical and that it makes no difference whether one uses calculated or measured soil heat values. However, this is not the case as can be seen when considering Fig. 2, 3, 4, and 5 which show that the computed slopes have nothing more than mathematical meaning. Since these graphs and tabular values do not exclude wild values, as is the case thereafter, it is of immediate interest to ask what these plots would look like with the wild values excluded and the day and night cases considered separately. This is shown in Fig. 6 and 7 for Station 2 and in 8 and 9 for Station 3. Here the picture is changed immediately and one sees that the night-time ratios are distinctly different from those of the day-time on either a classical or non-classical basis. Though neither the classical nor the non-classical case fits the data, the non-classical is a better fit for either station.

Referring back to Fig. 2, 3, 4, and 5 and considering the day and night cases separately with regard to the fitting, it can be seen that the same results apply qualitatively, although quantitatively the inclusion of wild data changes slope values slightly. Thus question 4 of the five questions pertaining to the general problem is answered—the ratios vary with thermal stability although we cannot deduce the nature of the variability from these tables and graphs.

It would be well at this time to look also at questions 1, 2, 3, and 5 inasmuch as they are not mutually exclusive of question 4.

> Question 1—Are the exchange coefficients equal?—Since we know the ratios vary with stability, this can be answered in the negative, unless one considers the possibility that the three coefficients vary in the same manner. This seems a rather remote possibility since it would imply that all conditions of heating, moisture, and forced convection are the same as far as the exchange coefficients are concerned.

> Question 2—Are the ratios of the exchange coefficients equal to

a constant value?—The answer is certainly negative, excluding the remote possibility still present for the affirmative in question 1.

Question 3—Are the ratios equal to the ratios of the molecular counterparts?—The answer is negative because of the stability variation.

Question 5—What is the functional definition of the exchange coefficients?—This cannot be answered.

The important question now to consider is the nature of the variability of the exchange coefficients which is reflected by the changes in slope for the various stability classifications. Looking first at the Bowen Ratio separations, as shown in tables 4 and 5 (and Fig. 6 through 9), it may be seen that the pattern of change is the same for stations 2 and 3 for the day-time cases and it is reasonable to suppose the pattern would remain the same for the night-time cases had the Station 3 data been computed. The second thing to note is that in the night-time cases the slope values are essentially constant whereas in the day-time cases there is first a pattern of increase with increasing Bowen Ratio and then a decrease, which, in spite of the data-scatter, would seem to be real even though it is doubtful that the three-place significance shown for these calculations is justified. This pattern is better seen in the corresponding figures which also give one an evaluation of the scatter.

However, while the Bowen Ratio may be used as an indication of stability in a broad sense, it is certainly not a clear-cut stability parameter and it is better to look at the Richardson number to see whether some systematic pattern of variation can be defined. Comparing tables 6 and 7 with tables 4 and 5 respectively, it may be seen that the same general situation is present, although it should not be inferred that this relates the Richardson number and the magnitude of the Bowen Ratio. As the Richardson number increases negatively (the day-time environment), there is an increase in the slopes of the lines of best fit for both classical and non-classical cases, although for the former the increase for values of the Richardson number less than minus .1 tends to level out for Station 2 but not for Station 3 where a greatly reduced number of cases are considered. For the night-time environment at either station or for either classification, the near-constancy of the slope coefficients is met again. Figures 10 and 11, which are summary diagrams for the results of tables 6 and 7, show, of course, the same trend as well as the degree of scatter. In these figures only the non-classical values are shown and the Richardson number variation from zero to .01 have been combined with the zero case.

Even though tables 6 and 7 (and Fig. 10 and 11) clearly show a variation of the ratios according to stability classifications as indicated by Richardson number, it would seem somewhat optimistic to attempt to quantitatively define this pattern of variation in view of the scatter of the data.

As noted earlier, only one study has been reported in the literature similar to the one described herein and that is the one by Halstead and Clayton utilizing data collected during diffusion releases on Project Prairie Grass at O'Neill, Nebraska. In this study the Halstead concept of the equivalence of the turbulent and laminar ratios was verified, which is in direct opposition to the findings of this paper. One factor that might account for this contradiction is that the former study consisted of only 48 cases covering only limited stability variations although there were night and day cases included. Also, if one refers to Fig. 5.3 and Fig. 5.4 of the Halstead-Clayton paper, one can see that a separation of night-time and day-time cases would not be unreasonable although the indication is not as clear as it is in this study.

Although this discussion is restricted to the qualitative aspects of the exchange coefficient ratios, it was interesting to consider what quantitative modification to the classical and non-classical assumptions would be required to provide the best fit for the data analyzed. Since this could only be a gross attempt in view of the poor indication of day-time variability of the ratios, it did not appear to be promising to evaluate this modification maintaining the day-time differences, and the computations were limited to night-time versus day-time. The calculations involved in arriving at these modifying figures (given in Table 8) are not shown herein but follow the method used by Lettau (1957) in his discussion of a Halstead paper based on data taken at O'Neill, Nebraska in 1954 (Project Great Plains). Lettau's values also are shown in Table 8 and while the individual values differ somewhat, the same day-time, night-time variability pattern is present.

It is not possible to explicitly state why the values derived from the two studies should be different although the difference undoubtedly rests in part on the fact that the Lettau values are for average

Table 8. Empirically determined values of ratios K_h/K_m and K_e/K_m from energy balance—Station 2.

Data Source	Day-time		Night-time	
	K_h/K_m	K_e/K_m	K_h/K_m	K_e/K_m
Green Glow	2.92	1.53	0.51	0.45
Great Plains	1.54	1.13	0.48	0.28

day-time and average night-time conditions, whereas the Green Glow valuations cover wider stability situations, particularly in the day-time, and a larger number of cases.

Aside from the behavior of the exchange coefficients with stability variation, one final observation should be made. Further use of mean values for the investigation of turbulent regimes should be approached with caution, not only from consideration of the sensors available (particularly those for vapor pressure, net radiation, and direct measurements of soil heat flux*), but also from the fact that, even with perfect instrumentation, the functional definition of the exchange coefficients cannot be resolved through the techniques employed in this and previous studies. Specifically, direct measurements of the energy fluxes will have to be made through observations of the anomalies from mean values for both horizontal and vertical wind, temperature, and vapor pressure. Only instrumentation capable of such

*It has been encouraging to the author to learn through direct association with the Dallas Tower Program, currently underway, that a concerted effort is being made to improve the quality of the sensors being used for these measurements.

measurements coupled with mean measurement systems can provide the data required for final resolution of questions concerning the vertical atmospheric transfer and in so doing provide understanding for the development of a realistic theory of turbulent flow in the atmosphere.

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Final Report prepared by William H. Clayton and Purachand D. Mistry. Air Force Contract AF 19(604)-5527.

This report, aside from a brief review of project tasks, covers a study of the turbulent exchange coefficients based on energy balance and mean flow parameters measured at Project Green Glow. This study reveals that the ratio of the exchange coefficients are functionally related to thermal stability, thereby contradicting those postulates which have assumed constancy of the ratios for all stability situations.

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2. Micrometeorology
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